

Suppression of higher-order modes in aircore microstructure fiber designs

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Abstract: Modified designs for hollow-core bandgap fibers with suppressed higher-order modes are proposed. Numerical simulations demonstrate that index-matched cladding defects can dramatically increase losses of undesirable modes and leave the fundamental well confined.

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1. Introduction

Progress in aircore and other bandgap fibers demonstrates that they can combine many of the material and manufacturing advantages of the standard fiber draw process with unique capabilities not possible in standard fibers. Aircore fibers have particularly interesting potential in data transmission, since the nonlinearity of aircore fibers is much smaller than standard fibers, dramatically changing the cost and performance of a transmission link. However, any long-distance transmission fiber must compete against the extremely low loss of standard fibers. Despite rapid improvements, it has been suggested that aircore fiber losses are approaching a fundamental limit [1], and can only be improved further by increasing the core size or finding improved materials. It is then very desirable to move to larger core sizes, but this generally introduces problems due to higher-order modes.

We propose a strategy for suppression of higher order modes of bandgap fibers based on index-matched coupling between core modes and cladding modes. By introducing appropriate cladding features near the core, light in the higher-order modes can be made to resonantly couple between core and cladding, while light in the fundamental remains well confined. For the proposed designs, introduction of cladding features (in an otherwise periodic cladding) significantly increases the loss of higher-order modes, with essentially no impact on the fundamental-mode confinement. This removes a significant obstacle in the development of larger-core single-mode designs, and may allow aircore fibers to surpass the loss of standard fibers.

2. HOM suppression by resonant core-cladding coupling

One basic strategy for managing higher-order modes is to induce loss in these modes. If these modes see enough loss, they are “suppressed” or “effectively cutoff,” which can improve system performance by reducing noise, coupling to the signal mode, etc. Figure 1 illustrates the concept of HOM suppression through index-matched coupling. In the index plot (left), hatched regions indicate that bandgaps exclude light from the periodic cladding of the fiber. Two defect regions, the core and a cladding defect, have guided modes with fields depicted by solid curves. When the effective indices (dashed lines) for a core mode and cladding mode are nearly equal, these modes will efficiently couple. In a desirable HOM-suppressed design, the fundamental mode remains well confined to the core, but light will couple from the unwanted higher-order core modes to the defects and subsequently be lost. A similar approach for index-guided fibers has been discussed recently [2]. The schematic geometry (right) shows that the strategy can be implemented in a 1D radial Bragg-fiber bandgap structure as well as the 2D-lattice structures chosen for the following examples.

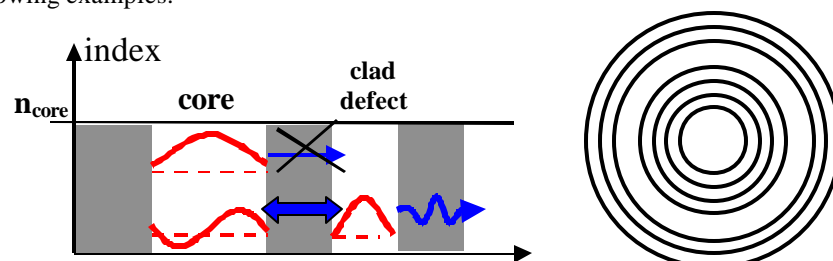


Fig. 1. Higher-order modes can be suppressed in a bandgap fiber using the mechanism of index-matched coupling between core and cladding. The higher-order core mode is index-matched to the defect mode, and so will be selectively suppressed relative to the fundamental mode.

3. Simulation results

To demonstrate this strategy numerically, we start with the most common type of aircore fiber studied experimentally and theoretically, and then add additional defects to the core according to the index-matching strategy. Figure 2 (top left) shows the “standard” aircore structure: a large air hole surrounded by a triangular lattice of smaller air holes in a silica substrate. The normalized hole size was $d/\Lambda = .94$, and hole spacing was $\Lambda = 2.5$ microns. The core is formed by simply removing glass within a central circular region of radius 4.25 microns, as, for example, in [3]. The HOM-suppressed design (bottom left) is the same as the “standard” design, but ten of the glass vertices that make up the lattice are removed from each of the two defect locations. Guidelines for avoiding surface modes [3] were generalized so that a non-circular surface-mode-free cladding defect could be constructed. For this particular core and defect shape, the fundamental air-guided defect mode has an effective index very close to the first group of higher-order core modes. Other core and defect shapes may be more easily fabricated, and should follow the same conditions: providing index matching while minimizing surface modes at both core and cladding defect. Simulations were done with a finite difference mode solver very similar to [4].

Calculated confinement losses for the standard and HOM-suppressed designs confirm the design strategy. Figure 2 shows that both aircore designs have a bandgap and low-loss air-guided fundamental (bottom solid and dashed lines) near 1550nm wavelength. The standard fiber losses (dashed) show low-loss HOM modes over much of the bandgap, an indication that HOMs will be problematic. For the HOM-suppressed design (solid), however, the HOM loss has been substantially increased, with no corresponding increase in fundamental loss. This can substantially increase the usable bandwidth of the fiber: for example, if we assume the system requirement is fundamental loss less than 10dB/km and HOM loss greater than 200dB/km, the standard fiber has only a 25nm useable bandwidth (shaded grey region), compared with 91nm for the proposed fiber (black rectangle). Intensity plots (bottom, for HOM modes at 1538nm) highlight the mode-coupling mechanism responsible for HOM suppression. For the standard design, the HOM is well confined to the core region, and has little leakage through the cladding. For the proposed design (bottom right), the intensity shows a small peak at the cladding defect. This indicates light coupling from the core to the cladding, which subsequently experiences much larger leakage to radiation.

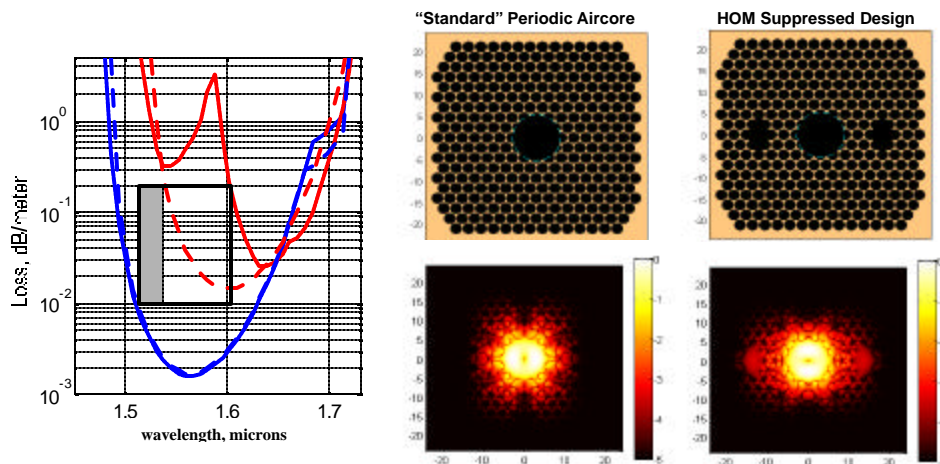


Fig. 2. Simulations demonstrate that undesirable higher-order modes of a standard aircore fiber can be substantially suppressed using a modified design. The loss plot (left) shows that the fundamental loss is essentially the same for both designs (lowest dashed and solid curves), but that the HOM loss is much larger for the modified fiber (upper solid curve) than for the standard fiber (upper dashed curve). The geometry and HOM intensity plots (right) show a small but important intensity peak at the cladding defect (highlighted by a log₁₀-scale color map) for the modified design.

4. References

1. P. J. Roberts, F. Couny, et al., “Ultimate low loss of hollow-core photonic crystal fibres,” *Opt. Express*, **13**, 236 (2005).
2. J. M. Fini, “Design of solid and microstructure fibers for suppression of higher-order modes,” *Opt. Express* **13**, 3477 (2005).
3. Hyang Kyun Kim, Jonghwa Shin, et. al., “Designing air-core photonic-bandgap fibers free of surface modes”, *J. Quantum Electron.*, (2004).
4. S. Guo, F. Wu, et. al., “Loss and dispersion analysis of microstructured fibers by finite-difference method,” *Opt. Express* **12**, 3341 (2004).